Is the magnetic field necessary for the Aharonov-Bohm effect in mesoscopics ?

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Abstract

We predict a new class of topological mesoscopic phenomena in absence of external magnetic field, based on combined action of the nonequilibrium nuclear spin population and charge carriers spin-orbit interaction (meso-nucleo-spinics). We show that Aharonov-Bohm like oscillations of the persistent current in GaAs/AlGaAs based mesoscopic rings may exist, in the absence of the external magnetic field, provided that a topologically nontrivial strongly nonequilibrium nuclear spin population is created. This phenomenon is due to the breaking, via the spin-orbit coupling, of the clock wise - anti clock wise symmetry of the charge carriers momentum, which results in the oscillatory in time persistent current.

PACS: 73.20.Dx; 31.30.Gs; 71.70.Ej

Persistent currents (PC) in mesoscopic rings reflect the broken clock wise-anticlock wise symmetry of charge carriers momenta caused, usually, by the external vector potential. Experimentally PCs are observed when an adiabatically slow time dependent external magnetic field is applied along the ring axis [1–3]. The magnetic field variation results in the oscillatory, with the magnetic flux quantum $\Phi_0 = \frac{hc}{e}$ (or its harmonics) period behavior of the diamagnetic moment (the PC), which is the manifestation of the Aharonov-Bohm effect (ABE).

We propose here that in a quantum ring with a nonequilibrium nuclear spin population the persistent current will exist, even in the absence of external magnetic field. We predict the ABE like oscillations of PC with time, during the time interval of the order of nuclear spin relaxation time T_1 [4], which is known to be long in semiconductors at low temperatures [5]. The hyperfine field , caused by the nonequilibrium nuclear spin population [5] breaks the spin symmetry of charged carriers. Combined with a strong spin - orbital (SO) coupling, in systems without center of inversion [6,7] , it results in the breaking of the rotational symmetry of diamagnetic currents in a ring. Under the topologically nontrivial spatial nuclear spin distribution, the hyperfine field produces an adiabatically slow time variation of the Berry phase of the electron wave function, analogous to one which emerges in standard ABE in textured mesoscopic rings [8,9] and in Aharonov-Casher effect [10]. The time variation of this topological phase results in observable oscillations of a diamagnetic moment (the persistent current). We emphasize that this is one of a series of "meso-nucleo-spinic" effects, which may take place in mesoscopic systems with broken, due to the combined action of the hyperfine field and spin-orbital interaction, symmetry.

The hyperfine interactions in GaAs heterojunctions and similar quantum Hall systems attracted recently sharply growing theoretical [14] and experimental [15–17] attention. The main recent physical interest in this subject is based on a fact that

the discrete nature of the electron spectrum in these systems will result in exponentially long: $T_1 \sim \exp\{\Delta/T\}$ (here Δ is the electron energy level spacing and T is the temperature) dependence of the nuclear spin relaxation times T_1 on the system parameters, [14]. We assume here that similar law should take place also in the nanostructures with well defined size quantization of the electron spectrum. Note that in this case T_1 is very sensitive to the potential fluctuations, caused by the inhomogeneous distribution of impurities in a heterojunction [20] . Intensive experimental studies [15–17] of this phenomenon have provided a more detailed knowledge on the hyperfine interaction between the nuclear and electron spins in heterojunctions and quantum wells. It was observed that the nuclear spin relaxation time is rather long (up to 10^3 sec) and the hyperfine field acting on the charge carriers spins is extremely high, up to $10^4 G$ [15,16]. Till now, however, the manifestations of the hyperfine interaction in quantum interference (mesoscopic) phenomena has not been studied.

Spin-orbit interaction plays an important role in mesoscopic physics. In disordered quantum rings it was studied in [11,12], where universal reduction of the PC harmonics was obtained. Similar conclusions were drawn in [13] where the SO interaction specific for a GaAs/AlGaAs heterojunctions was studied. We show here that in such systems SO combined with the hyperfine field, produced by strongly nonequilibrium nuclear spin population can play a constructive role in creating an analog to AB effect.

The contact hyperfine interaction is [4]:

$$\widehat{H}^{en}_{chf} = \frac{8\pi}{3}\mu_B \gamma_n \hbar^2 \sum_i \mathbf{I}_i \cdot \sigma \delta(\mathbf{r} - \mathbf{R}_i). \tag{1}$$

Here μ_B is the Bohr magneton, γ_n is the nuclear magneton, $\mathbf{I}, \sigma, \mathbf{R}_i, \mathbf{r}$ are the nuclear and the charge carriers spins and position vectors, respectively. It follows from Eq. (1), that once the nuclear spins are polarized, i.e. if $\langle \sum_i \mathbf{I}_i \rangle \neq 0$, the charge carriers

spins feel the effective, hyperfine field $B_{hypf} = B^o_{hypf} \exp(-t/T_1)$ which lifts the spin degeneracy even in the absence of external magnetic field. In GaAs/AlGaAs one may achieve the spin splitting due to hyperfine field of the order of the one tenth of the Fermi energy [15,16].

Let us suppose therefore that the charge carriers spin orientation is partially polarized during the time interval of the order of T_1 . It is quite obvious that the topologically nontrivial spin texture combined with the spin-orbit interaction will result in a persistent current.

The spin-orbit interaction in GaAs/AlGaAs heterostructures was widely studied both theoretically and experimentally (see [6] and references therein). The main contributions came from a) bulk inversion assymmetry and b) from the structure inversion asymmetry, first pointed out in [7] . Since both contributions are of comparable value, in what follows we will concentrate, for simplicity, on the typical for a heterojunction Bychkov-Rashba term [7]

$$\widehat{H}_{so} = \frac{\alpha}{\hbar} \sum_i \left[\sigma_i \times \mathbf{p}\right] \nu, \tag{2}$$

where $\alpha = 0.6 \cdot 10^{-9} eVcm$ for holes with $m^* = 0.5 m_0$ (m_0 is the free electron mass) [7,18], and $\alpha = 0.25 \cdot 10^{-9} eVcm$ for electrons [7,19], σ_i ,$\mathbf{p}_i$ are the charge carrier spin and momentum and ν is the normal to the surface. It can be rewritten in the form

$$\widehat{H}_{so} = \mathbf{p}\mathbf{A}_{eff}, \tag{3}$$

where

$$A^{GaAs}_{eff} \simeq \frac{\alpha m^*}{\hbar} \langle \sigma \rangle \,, \tag{4}$$

$\langle \sigma \rangle$ stands for a nonequilibrium carriers spin population. Under the conditions of a topologically nontrivial orientation of $\mathbf{A}^{GaAs}_{eff}$ (see the discussion below) the wave function of a charge carrier encircling the ring gains the phase shift similar to the

one in an external magnetic field like in the ordinary ABE. This phase shift can be estimated as follows

$$2\pi\Theta = \frac{1}{\hbar}\oint A_{eff}^{GaAs}dl = \frac{m^*}{\hbar^2}\left\langle \sigma(t)\alpha\right\rangle \sim \frac{m^*\sigma(t)\alpha}{\hbar^2}L, \tag{5}$$

where L is the ring perimeter. To observe the oscillatory persistent current connected with the adiabatically slow time-dependent $\langle\sigma(t)\rangle$, L is supposed to be less than the phase breaking length. Taking the realistic values for $L \approx 3\mu m$ [3] and $\langle\sigma\rangle \approx 0.05 \div 0.1$ [15,16] we estimate $2\pi\Theta \sim 5 \div 10$ which shows the experimental feasibility of this effect.

The standard definition of the spontaneous diamagnetic current is

$$j_{hfso} = -c\frac{\partial F}{\partial\phi}\mid_{\phi_{ext}=0}, \tag{6}$$

where F is the electron free energy and ϕ_{ext} is the external (probe) magnetic flux. The oscillations of persistent current arise due to the exponential time dependence of the phase $\Theta_{eff}^0 \exp\{-t/T_1\}$ in Eq. (5), with the time constant T_1.From the analogy with the standard ABE in a mesoscopic ring, we expect the following form for a persistent current in an one dimensional quantum ring at low enough (T $\ll \Delta$) temperature

$$j_{hfso} \sim \frac{ev_F}{L}\sin(2\pi\Theta_o e^{-\frac{t}{T_1}}). \tag{7}$$

Here Θ_o is the initial phase value. We outline the marking difference between the periodical time dependence of standard AB oscillations, which are observed usually under the condition of linear time variation of the applied magnetic field and the hyperfine driven oscillations which die off due to the exponential time dependence of the nuclear polarization.

In what follows, we present the microscopic justification of the qualitative model discussed above.

The microscopic description is based on a following Hamiltonian

$$\widehat{H}=-\frac{\hbar^{2}}{2m^{*}\rho^{2}}\left(\frac{\partial}{\partial\varphi}-i\frac{\Phi}{\Phi_{o}}\right)^{2}-i\frac{\alpha(\varphi)}{\rho}\left(\sigma_{z}\cos\varphi+\sigma_{y}\sin\varphi\right)\left(\frac{\partial}{\partial\varphi}-i\frac{\Phi}{\Phi_{o}}\right)$$

$$+i\frac{\alpha(\varphi)}{2\rho}\left(\sigma_{z}\sin\varphi-\sigma_{y}\cos\varphi\right)-\frac{i}{2\rho}\frac{d\alpha}{d\varphi}\left(\sigma_{z}\cos\varphi+\sigma_{y}\sin\varphi\right)-\mu_{B}B_{hypf}\sigma_{z}. \tag{8}$$

It describes the carriers, confined to an one-dimensional ring of radius ρ , placed in the (ZY) plane, in a case of inhomogeneous SO coupling which, as will be discussed later, is one of the possible realizations of a topologically nontrivial effective vector potential Eq. (4). The ring is pierced by an external magnetic flux Φ , B_{hypf} is the hyperfine field oriented along the Z -axis. Note, that the Hamiltonian, Eq. (8), is a generalization of $\alpha = const$, studied in [13] , for the case $\alpha = \alpha(\varphi)$.

Let us show, within the perturbation theory, that the l.h.s. of the Eq. (6) is nonzero at $\Phi = 0$. Since the electron Zeeman splitting in GaAs/AlGaAs, caused by the hyperfine field, B_{hypf} at strongly nonequilibrium nuclear population, exceeds $\alpha\hbar/\rho$ in micron rings, we may safely neglect the effective spin-orbital field compared to the hyperfine one. The zero-approximation eigenfunctions and eigenvalues are, respectively

$$\Psi_{n}^{(\pm)}=\frac{1}{\sqrt{2\pi}}\left(\begin{pmatrix}1\\0\end{pmatrix},\begin{pmatrix}0\\1\end{pmatrix}\right)\exp\left(in\varphi\right);$$

$$\varepsilon_{n}^{(\pm)}=\frac{\hbar^{2}}{2m^{*}\rho^{2}}\left(n-\frac{\Phi}{\Phi_{o}}\right)^{2}\pm\mu_{B}B_{hypf}. \tag{9}$$

The flux-dependent first order corrections to $\varepsilon_n^{\pm}$ are

$$V_{nn}^{\pm}=\pm\frac{1}{4\pi\rho}\left(n-\frac{\Phi}{\Phi_{o}}\right)\int_{0}^{2\pi}d\varphi\alpha\left(\varphi\right)\cos\varphi=\pm\left(n-\frac{\Phi}{\Phi_{o}}\right)\frac{\langle\alpha\rangle}{\rho}. \tag{10}$$

It follows that each level carries current if the integral in the r.h.s. of the Eq. (10) is nonzero. This implies topological restrictions on the function $\alpha(\varphi)$which are equivalent to existence of a topologically nontrivial spin texture.

Calculation of the first order correction to the free energy is straightforward, and using the Eq. (6) the spontaneous persistent current can be found to be

$$j_{hfso} \simeq \frac{c\Delta}{\rho\Phi_0 T}\left\langle\alpha\right\rangle\sum_{n=0}^{\infty}n^2\left\{\cosh^{-2}\left(\frac{n^2-\mu_-}{T^*}\right)-\cosh^{-2}\left(\frac{n^2-\mu_+}{T^*}\right)\right\}, \tag{11}$$

here $\Delta = \hbar^2/2m^*\rho^2$;$\mu_\pm = \left(\mu \pm \mu_B B_{hypf}\right)/\Delta$, where μ is the chemical potential, $T^* = T/\Delta$.

At low temperatures: T$\ll \Delta \ll \mu_B B_{hypf} \ll \mu$, the Eq. (11) reads

$$j_{hfso} \simeq \frac{2ev_F\left\langle\alpha\right\rangle\left\langle\sigma\right\rangle m^*}{\hbar^2} \sim \frac{ev_F}{L}\Theta\left(t\right) \tag{12}$$

where

$$\left\langle\sigma\right\rangle = \frac{\mu_B B_{hypf}}{\mu} \tag{13}$$

is the nonequilibrium spin population introduced in the Eq. (4), and $\Theta\left(t\right)$ is the topological phase Eq. (5). We note, that Eq. (12) is the first term of the expansion of the phenomenological equation Eq. (7) . It follows, that the direct quantum mechanical calculation confirms the existence of a spontaneous persistent current, induced by combined action of the nonequilibrium nuclear spin population and spin-orbit coupling.

Consider now the possibility of creation of a topologically nontrivial effective vector potential defined in Eq. (5) . In the geometry where the vector ν , Eq. (2), is normal to the heterojunction, either the nuclei polarization driven $\sigma\left(\varphi\right)$ or the spin-orbit coupling $\alpha\left(\varphi\right)$should be inhomogeneous along the perimeter of the ring. Out of a variety of different experimental realizations let us outline the following ones.

Since the nuclear relaxation rate T_1^{-1} in GaAs/AlGaAs heterojunction is highly sensitive to the impurities distribution [20], one can achieve different nuclear polarization in different parts of a mesoscopic ring, provided the characteristic length of the impurity potential is of order of several hundreds of A , i.e. comparable to the ring width. In this configuration we expect that the mesoscopic sensitivity to a single impurity position may produce a nonvanishing phase Eq. (5).

Another way of obtaining a nonzero circulation of the effective vector potential is creation of the slowly varying on the scale k_F^{-1} coordinate dependent spin-orbit coupling $\alpha\left(\varphi\right)$connected with external potentials like boundaries, heavy atoms impurities along the perimeter of the ring and other imperfections which may locally modify the spin-orbit interaction in these systems.

To summarize, we propose here a new, hyperfine field driven (meso-nucleo-spinic) mesoscopic effect : the Aharonov-Bohm like oscillations of a persistent current in a GaAs/AlGaAs mesoscopic ring in the absence of external magnetic field. We note that the large (of the order of 1Tesla) hyperfine field results in the nonequilibrium population of the charge carriers spins. The latter, under the conditions of the topologically nontrivial spatial effective vector potential distribution results in a persistent current. This current is oscillating (aperiodically) and decreasing with time during the time interval of the order of the nuclear spin-relaxation time T_1. At low temperatures T_1^{-1} can be sufficiently long and the predicted oscillations experimentally observable..

We acknowledge illuminative discussions with H. Bednarski, Yu. Bychkov, A. Dyugaev, V. Gurevich, I. Krive, G. Kventzel', T. Maniv, L. Levy and B. Spivak.

I.V. acknowledge the support by US-Israeli Binational Science Foundation grant No. 94-00243.

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